Ultrafast modulation of semiconductor lasers through a terahertz field

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We demonstrate, by means of numerical simulation, an interesting mechanism to modulate and switch semiconductor lasers at THz and sub-THz frequency rates. A sinusoidal terahertz field applied to a semiconductor laser heats the electron-hole plasma and consequently modifies the optical susceptibility. This allows an almost linear modulation of the output power of the semiconductor laser and leads to a faithful reproduction of the terahertz-field waveform in the emitted laser intensity. © *1999 American Institute of Physics.* [S0003-6951(99)04330-2]

Semiconductor laser modulation and switching via the pumping current at gigahertz (GHz) rates is based on the so-called relaxation oscillation.[1,2] Physically, relaxation oscillation describes the periodic energy exchange between the laser field and semiconductor, which is an interband process dominated by stimulated electron-hole pair recombinations at high pumping level and occurs on a nanosecond time scale. For many applications, modulation and switching at higher rates is highly desirable. While improvements in modulation speed due to quantum well (QW) structure designs and other means have been quite impressive, further improvements beyond tens of GHz seem to be more difficult. The fundamental limit is placed by the slow interband carrier dynamics. While current modulation has the unique property that allows direct and simple modulation, other means to modulate and switch a diode laser at higher rates are under intensive investigation. Notable examples are switching due to nonequilibrium carrier dynamics under femtosecond optical excitation.[3–5]

In this letter, we report an alternative scheme for modulating and switching semiconductor lasers by employing terahertz (THz) frequency electric fields. Recent years have seen a surge of interest on the interaction of THz waves with QWs, and THz-field generation by semiconductor heterostructures. Moreover, our research is motivated by an experimental demonstration of heating of an electron gas by applying a THz driving field (henceforth denoted by TDF).[6] The experiment demonstrated that even under strong THz irradiation, the electron gas maintains essentially a heated, thermalized form. Subsequent theoretical works[7–9] showed that the heated plasma has an almost sinusoidal temperature variation with time with a frequency given by twice that of the TDF. Additionally, the associated gain and refractive index change due to the plasma heating effect induced by a half-cycle THz field can also lead to efficient transient optical modulation and may form the basis for an ultrahigh-speed all-optical switch.[9]

The purpose of this work is to demonstrate that a con-

tinuous TDF can induce a modulated power output from a semiconductor laser with a temporal modulation that faithfully follows the driving field. We consider a standard edge-emitting semiconductor laser with a QW active medium. In addition to a standard QW edge-emitting laser geometry, a TDF is applied such that the polarization is in the plane of QW layer. Such a TDF can be applied from a free-space THz source or by integrating the laser with a photoconductor and THz transmission structure. Our theoretical approach starts with the following equation for the carrier distribution function $n_{\mathbf{k}}^{\alpha}$

$$\left(\frac{\partial}{\partial t} + e\mathbf{F}_{\text{THz}}(t,\mathbf{r})\cdot\nabla_{\mathbf{k}}\right)n_{\mathbf{k}}^{\alpha} = \frac{\partial n_{\mathbf{k}}^{\alpha}}{\partial t}\bigg|_{c-c} + \frac{\partial n_{\mathbf{k}}^{\alpha}}{\partial t}\bigg|_{c-ph}$$
$$+ \frac{\partial n_{\mathbf{k}}^{\alpha}}{\partial t}\bigg|_{st} + \frac{\partial n_{\mathbf{k}}^{\alpha}}{\partial t}\bigg|_{rest}, \qquad (1)$$

where $\alpha = e(+\mathbf{k}), h(-\mathbf{k})$ for electrons and holes, respectively, and F_{THz} is the THz field. The first two terms in the right hand side of Eq. (1) represent carrier-carrier (c-c) and carrier-phonon (c-ph) scattering, while the third term accounts for stimulated recombination and the last term for pumping and other decay processes. We note that the TDF creates highly anisotropic carrier distributions ($n_{k_x} \neq n_{k_y}$) which must be solved for on a two-dimensional mesh of $\mathbf{k}$ points. Though a self-consistent many-body calculation of such anisotropic scattering terms is feasible, it involves a significant computational effort, and thus we restrict ourselves to the standard relaxation-rate approximations for both of the c-c and c-ph scattering in this letter. The relaxation times (inverse of the relaxation rates) are chosen as 100 fs for c-c and 600 fs for c-ph scattering for the 30 K simulations and 50 and 300 fs, respectively, for the 300 K simulation. Many-body interactions are not considered in this letter and the related effects will be discussed in a more detailed investigation. For this letter, the THz waveform is assumed to be sinusoidal. The results, however, carry over to more general temporal waveforms that may be of interest for switching and modulation with a signal field.

For the description of the semiconductor laser, we employ a well-tested rate-equation model except we add additional terms for the TDF-induced plasma-heating effects. Under the rate-equation approximation, which essentially amounts to ignoring the polarization dynamics of the medium, the basic equations take the form:

$$\frac{\partial E}{\partial t} = \frac{iKc}{2n_g}\Gamma\chi(N,T)E - \kappa E, \qquad (2)$$

$$\frac{\partial N}{\partial t} = \frac{J}{ew} - \gamma_N N + \frac{\epsilon_0\epsilon_b}{2\hbar}\chi''(N,T)|E|^2, \qquad (3)$$

where the symbols have their usual meanings: J, w, and Γ are the pumping current, active medium thickness, and the confinement factor; K, n_g, and ϵ_b are the optical wave vector, group index, and background dielectric constant; κ is the cavity relaxation constant; E is the slowly varying amplitude of the laser field, and $N = 2\Sigma_k n_k^\alpha/V$ is the carrier density for electrons and holes which are assumed the same. The optical susceptibility, $\chi = \chi' + i\chi''$, can be written as (linear approximation):[10]

$$\chi(N,T) = \chi(N_0,T_0) + \frac{\partial\chi}{\partial N}(N-N_0) + \frac{\partial\chi}{\partial T}(T-T_0). \qquad (4)$$

We assume that the effects of the constant $\chi(N_0,T_0)$ are absorbed into the cavity decay constant κ. The above expression can subsequently be cast into the following form by introducing the density and temperature α-factors:[10]

$$\chi(N,T) = -ia_N(N-N_0)(1-i\alpha_N) - ia_T(T-T_0)(1-i\alpha_T). \qquad (5)$$

A few words about the model are in order. To start from a more fundamental level, we need to solve the Boltzmann equations coupled to the optical field and TDF as well as to the optical polarization. This would correspond to the semiconductor Bloch equations (SBEs)[11] with an additional THz field. The coupling of such SBEs with the wave equation for the optical field will offer a more complete framework for studying the interplay between the TDF, optical field, charge carriers, and phonons in a semiconductor. For lasers, a systematic approximation along the line of moment equations would be more feasible.

Our present approach, represented mainly by Eqs. (2) and (3) can be justified in the following way. First, we ignore the heating effect due to stimulated emission of optical photons, as this heating is much less important for lasers slightly above threshold than heating due to the TDF. This allows a simplification of the coupling between the heating and lasing processes; heating due to the THz field will influence lasing, but not *vice versa*. Under this approximation, the set of moment equations will be reduced to Eqs. (2) and (3) if we further assume that the relaxation of the average momentum and energy is much faster than the relaxation of the total carrier density and laser field. Due to this simplification, we can solve Eq. (1) for a given carrier density separately. The resulting distribution will be fitted to a Fermi function which thus determines the plasma temperature at a given density under the influence of the THz field. Such a calculation allows us to obtain the temporal variation of the plasma temperature on the time scale of the TDF. The underlying as-
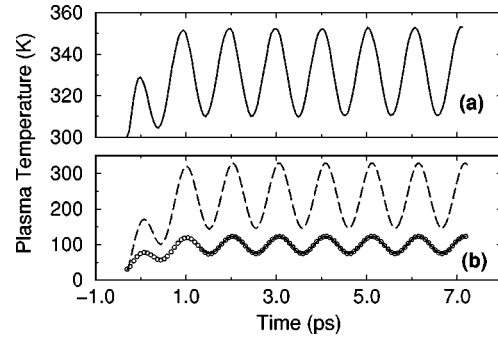

FIG. 1. Plasma temperature oscillation by means of a terahertz driving field. (a) Lattice temperature is 300 K and the field amplitude is 5 KV/cm. (b) Lattice temperature is 30 K and field amplitude values: 2.5 kV/cm (circles) and 5.0 kV/cm (dashed lines). The solid line is fitting as explained in the text.

sumption is that carriers after accelerating will thermalize quickly through c-c and c-ph scattering and a well-defined temperature will oscillate with the TDF. This is a valid assumption due to the subpicosecond scattering processes and is also established experimentally in Ref. 6.

Figure 1 shows typical examples of the temperature evolution by application of TDFs with an amplitude of 2.5 kV/cm [circles in Fig. 1(b)] and 5.0 kV/cm [Fig. 1(a), and dashed lines in Fig. 1(b)]. We see that after a rapid initial temperature increase from the lattice temperature [300 K in (a) and 30 K in (b)], the plasma temperature is stabilized within ~ 1 ps to a sinusoidal form. The time dependence of the temperature as a solution of the Boltzmann equation after the initial transients can be fitted to the form:

$$T = T_0(F_{THz}) + T_{am}(F_{THz})\cos(4\pi\nu_0 t + \phi_0), \qquad (6)$$

where ν_0 is the frequency of the TDF. As shown by the solid line in Fig. 1, the fitting is almost indistinguishable from the actual data. Similar behavior for a stronger field ($F_0 = 5.0$ kV/cm) is depicted by the dashed curve. This time dependence of the plasma temperature is consistent with those seen in another theoretical work.[8] The T_0 and T_{am} values are similar to those measured experimentally and calculated theoretically.

In the following, we assume that the time dependence of the plasma temperature is given by Eq. (6). To study the effects of the time-dependent plasma temperature, we solve Eqs. (2) and (3) numerically for a typical edge emitting diode laser. As a first example, we consider a laser of 200 μm in length with cleaved facets at both ends. The power reflectivity is assumed to be 35% for both facets. The active region consists of three QWs of 10 nm in width. The values of the α_N and α_T, taken from Ref. 10, are 3 and 2, respectively, which are typical values for infrared quantum well lasers. The value of the differential gain a_N, 5×10^{-15} cm^2, is taken from page 222 of Ref. 11, while a_T, computed from the microscopic theory is 10.8/cm K. In all our following examples, we use the values of $T_0 = 130$ K and $T_{am} = 40$ K. These parameters correspond to temperature oscillations at 30 K. We point out, however, that temperature modulation of more than 40 K in Fig. 1(a) at room temperature can lead to a gain modulation of about 500 1/cm. This much of gain modulation can induce quite deep laser modulation under proper dc bias. The basic mechanism demonstrated in this
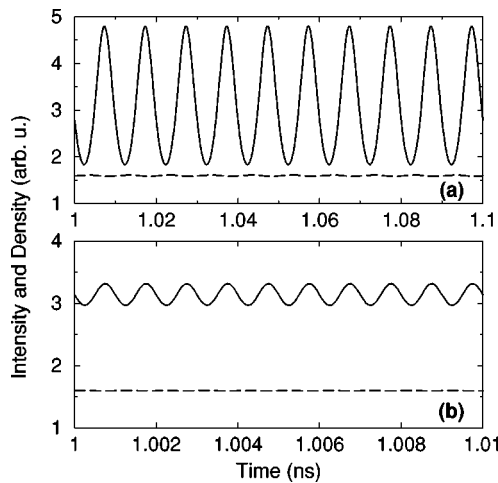
FIG. 2. Laser intensity (solid lines) and carrier density (dashed lines) vs time in the presence of a terahertz driving field of frequency (a) 50 GHz and (b) 500 GHz.

FIG. 3. As in Fig. 2 but with a field frequency of (a) 5 GHz and (b) 25 GHz.

letter therefore should not be limited to a particular temperature range. Figure 2 shows the laser intensity (solid lines) and carrier density (dashed lines) for two cases. In Fig. 2(a), F_{THz} is modulated at 50 GHz, while the corresponding frequency of the laser intensity is 100 GHz. We recognize from the figure that there is a regular sinusoidal oscillation with a deep modulation, while the carrier density shows only a slight wiggle. In Fig. 2(b), the frequency is increased to 0.5 THz. The intensity yields the same regular oscillation, but the modulation depth is significantly smaller than in Fig. 2(a); additionally, the carrier density is now a constant over many oscillation cycles, indicating that the slow interband recombination is not involved in this fast modulation.

With a further increase in the frequency of the TDF, the same regular intensity oscillations are observed. The modulation depth, however, decreases. For a frequency of a few THz, our model needs to be modified. In Fig. 3 two examples of *low* frequency TDFs are shown. As the temperature oscillation frequency decreases, the coupling with the carrier dynamics becomes important, since there is a near resonant interaction between the plasma temperature oscillation and the relaxation oscillation which is of the order of a few GHz. Figure 3(a) clearly shows signatures of such an effect. Consequently, the intensity-oscillation pattern is modified and the carrier density changes appreciably during the intensity oscillation. For the slightly higher temperature-oscillation frequency in Fig. 3(b) (25 GHz), we see a deeper modulation. Now the laser is almost switched off. The intensity pattern of Fig. 3(b) also shows a period-doubling phenomenon. This is again caused by an interplay between the carrier and temperature dynamics.

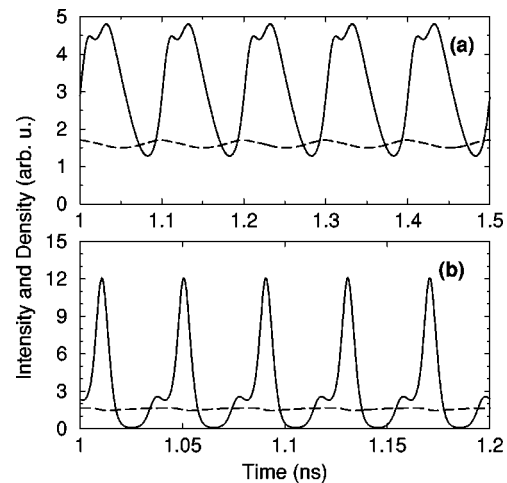To conclude, we have illustrated an ultrafast scheme to modulate and switch semiconductor lasers at THz and sub-THz frequency rates. This is possible by circumventing the usual slow interband carrier dynamics. We show that under a sinusoidal TDF, the temporal pattern of the electrical field can be converted to a similar, quite regular pattern of the laser intensity. This faithful representation of the sinusoidal THz field by a laser intensity pattern in the visible or infrared domain may offer an alternative way of measuring high-frequency alternating electrical fields. For lower-frequency oscillation, the same arrangement can lead to an almost 100% modulation and even on-off switching behavior. This could be useful for switching semiconductor lasers. Currently, we are conducting a more detailed study using the moment equations mentioned above.

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